SOIL HYDROLOGICAL RESPONSE UNDER SIMULATED RAINFALL IN THE DEHESA LAND SYSTEM (EXTREMADURA, SW SPAIN) UNDER DROUGHT CONDITIONS

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ABSTRACT

Soil hydrology was investigated in the Guadelperalón experimental watershed in order to determine the influence of land use and vegetation cover on runoff and infiltration within the Dehesa land system. Five soil–vegetation units were selected: (1) tree cover, (2) sheep trials, (3) shrub cover, (4) hillslope grass and (5) bottom grass.

The results of the simulated rainfall experiments performed at an intensity of 53·6 mm h^{-1} during one hour on plots of 0·25 m^2, and the water drop penetration time test indicate the importance of water repellency in the Dehesa land system under drought conditions. Low infiltration rates (c. 9–44 mm h^{-1}) were found everywhere except at shrub sites and in areas with low grazing pressure. Soil water repellency greatly reduced infiltration, especially beneath *Quercus ilex* canopies, where fast ponding and greater runoff rates were observed.

The low vegetation cover as a consequence of a prolonged drought and grazing pressure, in conjunction with the soil water repellency, induces high runoff rates (15–70 per cent). In spite of this, macropore fluxes were found in different locations, beneath trees, on shrub-covered surfaces, as well as at sites with a dominance of herbaceous cover. Discontinuity of the runoff fluxes due to variations in hydrophobicity causes preferential flows and as a consequence deeper infiltration, especially where macropores are developed. © 1998 John Wiley & Sons, Ltd.

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INTRODUCTION

Hydrological and erosional processes are currently being investigated in the Guadelperalón catchment. A general objective is to determine how soil properties, vegetation and land use influence runoff and erosion at different scales of time and space in the Dehesa land system.

Dehesas are open evergreen managed forests with a predominance of holm oaks and cork oaks. They are characterized by multiple land use: livestock, forestry, cultivation and hunting. This traditional land use system has evolved as an adaptation to the poor soils and adverse rainfall conditions, which cannot support intensive agricultural use. Cultivation, of minor importance in the Dehesas, is restricted to areas with better soil conditions. Dehesas constitute about 50 per cent of agriculturally used land in southwest Spain, occupying more than six million hectares (Campos and Martín, 1987) (Figure 1). Similar land use systems are found in other Mediterranean countries, and are under crisis from an economical point of view because of their low productivity (Campos and Manuel, 1989; Diaz, 1989).

Past research in the Dehesa has focused on the following: the decomposition rate of *Quercus ilex* leaves, the nutrient cycle (Escudero *et al*., 1981), the influence of *Quercus ilex* litter on soil development (Escudero *et al*., 1980a,b; Gómez-Gutiérrez *et al*., 1980), the variation and structure of grassland related to grazing intensity, the underground phytomass dynamics (Gómez-Gutiérrez and Barrera, 1986), and matter transfer by cattle (Gómez-Sal *et al*., 1992). Growing awareness exists for conserving these landscapes because of their great ecological

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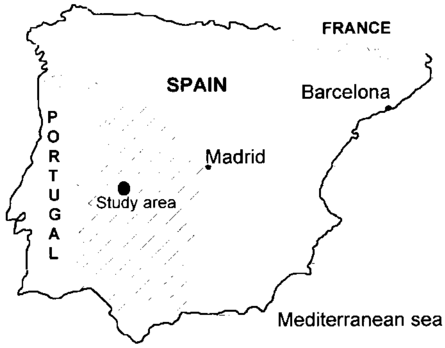

Figure 1. Location map. The shaded area shows the distribution of the Dehesa land use system in Spain

value. However, little is known about actual geomorphological processes, soils and their hydrological behaviour taking place. Some research has been carried out on hillslope erosion (Gómez-Amelia and Schanbel, 1990; Schnabel and Gómez-Amelia, 1995), vegetation dynamics (Bernet, 1995), and gully erosion (Schnabel and Gómez-Amelia, 1996).

The interrelation between vegetation cover, rainfall characteristics and hydrological as well as erosional processes established for the Dehesa study catchment, does not fully explain the detected spatial and temporal variability of the geomorphological processes (Schnabel and Gómez-Amelia, 1995, 1996). Therefore, experiments with simulated rainfall were carried out in order to study the hydrological response of the soils during low frequency–high magnitude events. Rainfall simulations were performed with an intensity of 53·6 mm h^{-1} and a duration of one hour to reach the steady-state infiltration rate. Due to the low wettability of the soil especially beneath *Quercus ilex*, measurements of the top horizon hydrophobicity were carried out by means of the water drop penetration time (WDPT). The objective of this paper is to investigate the soil hydrological response of the Dehesa land system during a drought period. The importance of the soil water repellency on surface runoff generation is highlighted.

STUDY AREA

General overview

The study area, located northeast of the city of Cáceres (Extremadura, Spain) (Figure 1), is a representative zone of the Dehesas in the SW Iberian Peninsula. The Guadalperalón study catchment belongs to the basin of the Almonte river, a tributary of the Tajo river. Geomorphologically the area forms part of the Cáceres peneplain, an upper Miocene erosion surface (Gómez-Amelia, 1985). The main rivers are deeply incised in the schists and granites of the peneplain, giving rise to a gently undulating landscape with increasing slope gradients on approaching the main collectors. The Cambisols developed in the area are eroded in most parts to give rise to Leptosols. Generally, the soil texture is silty or sandy loam with low amounts of organic matter.

The climate is Mediterranean, with hot, dry summers and moderately cold, moist winters. Mean annual precipitation is 511 mm. The annual rainfall distribution shows a dry season lasting from June to September and a wet season from October to April. Interannual variability is high with maxima and minima of 1007 and 277 mm, respectively. Droughts with a duration of more than two years are a common feature. Their mean frequency is estimated to be 7·8 years (Schnabel, 1995).

The Guadalperalón experimental watershed

Investigations in the Guadalperalón catchment (35 ha) have been carried out since 1990. Its maximum altitude is 400 m above sea level. Soils developed on schists have a silty texture, poor structure and porosity and low organic matter content (1·5 per cent). However, a very dense, thin layer of roots exists in the upper part of the soil horizon. This characteristic is due to grazing, which reduces the above-ground biomass and favours the development of a protective network of roots.

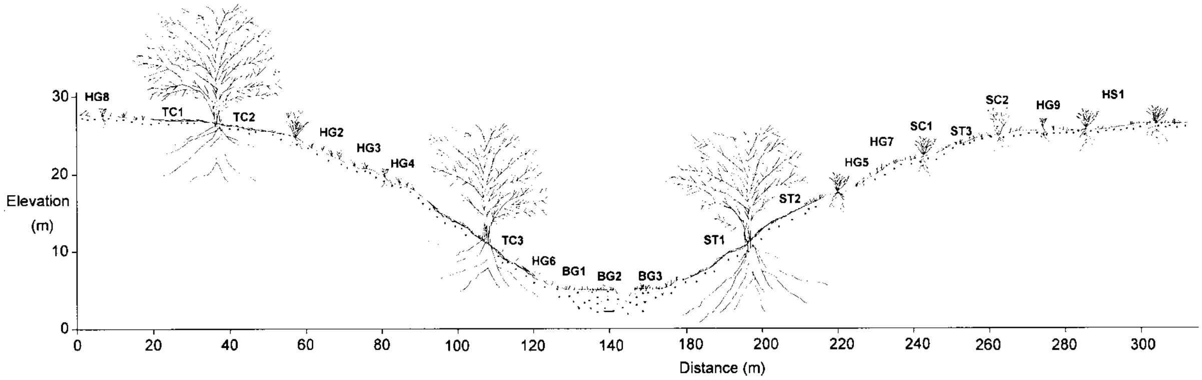

Figure 2. Sketch of the studied catena

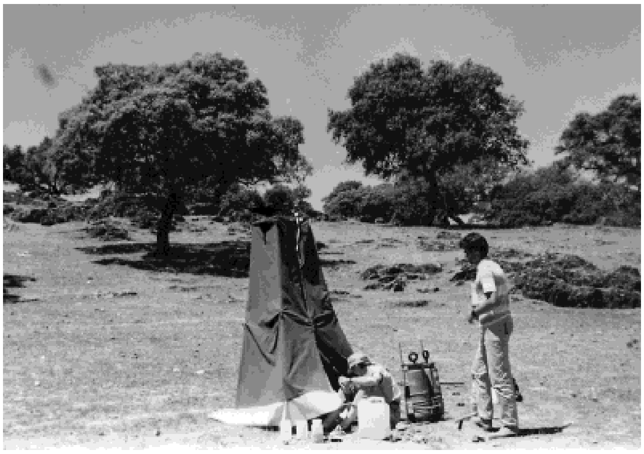

Figure 3. View of the rainfall simulator during the experiment

Areas with a tree cover (*Quercus ilex*) alternate with areas lacking trees. In the treeless zones soils are very shallow and the bedrock is exposed in many places. Vegetation is dominated by the shrub *Lavandula pedunculata* and a poorly developed herbaceous cover. On the tree-covered slopes (tree density 15 to 45 individuals per hectare), ground cover is dominated by herbs, and shrubs are less frequent (Figure 2). Soil depths range from 5 to 30 cm, but are higher at colluvial sites and in the valley bottoms filled with fluvio-colluvial sediments of up to 1·50 m thickness. Slope gradients range from 6 to 13°, increasing from the top to the bottom of the basin.

The more fertile and accessible parts of the catchment were cultivated in the past, but were abandoned 30 years ago. At present, land is grazed by sheep and a small number of pigs.

METHODS

The sites where rainfall simulation experiments and sampling were carried out were selected with regard to vegetation cover, soil characteristics and land use. The experiments were used to obtain the main soil hydrological characteristics, time to ponding, time to runoff, runoff coefficient at different time intervals (15, 30 and 60 min), steady-state infiltraton rate, changes in soil moisture, and the advance of the wetting fronts. For the experiments, a sprinkler rainfall simulator and the procedure described by Cerdà (1993a,b, 1995, 1996; Cerdà *et al*., 1995) was used (Figure 3). Rain was produced at an intensity of 53·6 mm h^{-1} over a 1 m^2 area. Runoff was measured from a 0·25 m^2 plot within the target area, in order to avoid border interferences. The duration of the experiments was 60 min, allowing the study of the process at different time intervals such as 15 or 30 min, which are much more frequent. Discharge from the plots was measured at 1–2 min intervals during the experiment.

Figure 4. View of a wetting front 10 min after the end of the rain: plot TC2

The 10 year return period rainfall with 1 h duration in the study area is estimated to be 25 mm (Schnabel, 1995), although greater values can be expected in Dehesa areas at higher altitudes (Elías and Ruiz, 1979). The estimated annual 30 min maximum rainfall intensity for 10 years is 42 mm h^{-1} and for 50 years is 56 mm h^{-1} in the nearest meterological station, Cáceres (Schnabel, 1997).

Twenty experiments were done during late May 1995, when the area suffered a prolonged drought. Measurements of soil moisture in the upper 3 cm were carried out by the gravimetric method at each site before and after the experiment. Ten minutes after the end of the rain, the plots were excavated (Figure 4) and the wetting front drawn. The data presented show only the central part of the plot (38 cm) in order to avoid interference caused by its border, i.e. 8·5 cm at each side were excluded.

Five different soil–vegetation units were studied:

(1) *Tree cover* (TC). Slope sites covered by the canopy of holm oaks. They are characterized by a very well developed litter layer of 2 to 4 cm (Figure 5a). Experiments TC1, TC2 and TC3.
(2) *Sheep trails* (ST). They only partially cover the plot due to the banded morphology of this feature (Figure 5b), and as a consequence interference from other surface types can be expected. Experiments on plots ST1 and ST2 are situated beneath trees and ST3 between trees.
(3) *Shrub cover* (SC). Located on the slopes without trees and covered by *Lavandula pedunculata* (Figure 5c). Experiments SC1 and SC2.
(4) *Bottom grass* (BG). Represents the valley bottom covered by herbaceous plants. Clear differences exist between the characteristics of the herbs from the valley bottom and the herbs from the slopes due to the different moisture regime (Bernet *et al*., 1994). In spite of the long dry period, the valley bottom still had a cover of green herbs (Figure 5d). Plots BG1 and BG2 are located in an overgrazed area, which is the normal situation in Dehesas during a drought situation, and plot BG3 is located in an area where livestock has been excluded for three years.
(5) *Hillslope grass* (HG). Located on sites not under the direct influence of a tree cover on the slopes. Plant cover was strongly reduced due to the drought (Figure 5c). Because it is the most widespread unit in the area, nine experiments were carried out there (HG1–HG9).

The parameter WDPT is the time required for complete infiltration of a drop placed on the surface of the soil (Letey, 1969; Crockford *et al*., 1991). Distilled water was used to produce drops of 1 g, and 310 measurements were done beneath trees and the same number between trees. The WDPT is directly related to the soil–liquid contact angle (Wessel, 1988), which is more difficult to measure (Letey *et al*., 1962; Fink, 1970).

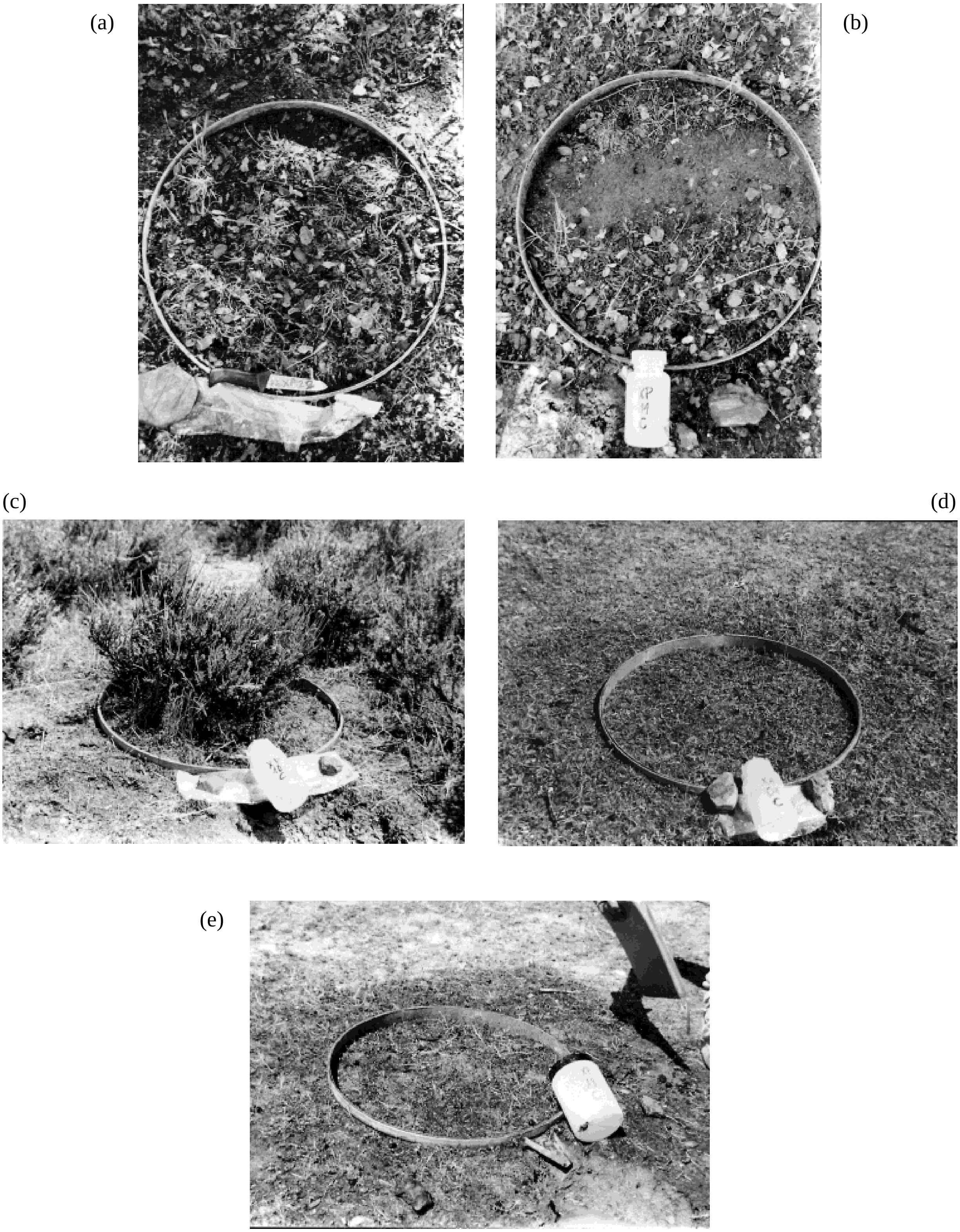

Figure 5. (a) View of plot TC3; beneath tree (*Quercus ilex*): Tree canopy cover. (b) View of plot ST1: Sheep trail. (c) View of plot SC2: Shrub cover (*Lavandula pedunculata*). (d) View of plot BG1; herb cover on the valley bottom accumulation: Bottom grass. (e) View of plot HG6; herb cover on the slope: Hillslope grass

Table I. Main soil surface characteristics at each plot

Plot	Aspect (°)	Slope (°)	Litter (%)	M+L (%)	Plant (%)	*Vh* (cm)	*Rfg* (%)	*Sd* (cm)
Hillslope grass								
HG1	170	12	1	1	12	1	15	40
HG2	90	10	35	2	4	1·5	2	70
HG3	90	13	10	2	5	1	5	40
HG4	90	14	10	30	2	2·5	20	35
HG5	250	12	1	1	5	3	8	26
HG6	80	11	2	25	10	2·9	2	40
HG7	260	12	8	2	1	2	15	30
HG8	90	12	25	10	2	1	0	20
HG9	60	17	50	10	5	3	1	30
Bottom grass								
BG1	180	2	5	0	90	1·8	10	>100
BG2	360	2	5	2	5	2·2	0	>100
BG3	180	2	30	35	90	42	0	>100
Tree cover								
TC1	60	10	75	0	10	3·4	5	40
TC2	57	6	30	5	5	3·4	0	20
TC3	100	18	75	5	6	3	0	70
Sheep trails								
ST1	280	12	30	7	5	3·2	4	5
ST2	280	15	25	10	10	2·2	6	16
ST3	60	8	5	10	2	1·8	5	45
Shrub cover								
SC1	280	11	40	1	80	30	1	23
SC2	265	11	25	0	80	15	75	32

M+L, mosses and lichen; *Vh*, vegetation height; *Rfg*, rock fragment cover; *Sd*, soil depth.

Table II. Mean values of the main soil surface characteristics for each soil surface type (abbreviations as in Table I)

Soil unit	Aspect (°)	Slope (°)	Litter (%)	M+L (%)	Plant (%)	*Vh* (cm)	*Rfg* (%)	*Sd* (cm)
Hillslope grass	131·11	12·56	15·78	9·22	5·11	1·99	7·56	46·22
Bottom grass	240·00	2·00	13·33	12·33	61·67	15·33	3·33	100·00
Tree cover	72·33	11·33	60·00	3·33	7·00	3·27	1·67	45·67
Sheep trails	206·67	11·67	20·00	9·00	5·67	2·40	5·00	22·00
Shrub cover	272·50	11·00	32·50	0·50	80·00	22·50	38·00	27·50

RESULTS

Plot surface characteristics

Table I shows the main soil surface characteristics of each plot and Table II the mean values of each soil unit. The north–south direction of the Guadalperalón valley explains the west or east aspects of the plots, while the ones located in the valley bottom have a north or south aspect. Slope gradients range from 6 to 18° on the slopes and are 2° on the valley floor. Mean slope angles of the soil units differ only a little (11–12·6°) except for the valley bottom.

Vegetation cover was very poor, except for the Shrub and the Bottom grass units. In some places, mosses and lichen have higher percentage cover than herbs. Litter cover is quite high, especially beneath trees and shrubs. Some of the Sheep trails are beneath trees, which explains their relatively high litter cover. Plant height is very low, except for the Shrub and the Bottom grass. Trees are not taken into account for this measurement.

Rock fragment cover of the soil surface is low (<8 per cent); only at the Shrub sites are values higher (38 per cent). Soil depth is highly variable, with the colluvial sites and the footslopes in general have the greater soil depths.

Table III. Soil surface response to the simulated rainfall at each plot

Plots	*tp* (min s)	*tr* (min s)	*ter* (min s)	*pr* (mm)	*wfd* (cm)	*Smb* (%)	*Sma* (%)
Hillslope grass							
HG1	3′00″	4′00″	2′10″	3·57	4·5	1·30	26·43
HG2	11′15″	13′00″	3′15″	11·61	7	1·08	29·25
HG3	6′30″	8′05″	2′00″	7·18	6	0·95	31·26
HG4	11′00″	12′50″	2′30″	11·16	7	1·01	27·16
HG5	3′00″	6′00″	2′45″	5·36	4	1·49	32·31
HG6	4′15″	5′00″	2′00″	4·46	5	2·81	30·73
HG7	3′30″	6′00″	2′10″	5·36	6	1·21	22·10
HG8	3′50″	5′00″	3′10″	4·46	3	2·87	26·47
HG9	5′30″	6′00″	1′30″	5·36	10	4·14	21·19
Bottom grass							
BG1	5′00″	6′20″	3′25″	5·90	2	12·04	37·20
BG2	4′30″	5′38″	4′00″	4·80	3	4·53	24·52
BG#	8′00″	9′00″	4′32″	8·04	10	7·88	35·48
Tree cover							
TC1	2′20″	3′19″	4′00″	2·85	1·5	0·89	26·90
TC2	1′15″	4′00″	2′10″	3·57	5	1·86	24·67
TC3	5′30″	6′00″	2′27″	5·36	12	2·74	34·70
Sheep trails							
ST1	4′45″	7′30″	2′34″	6·52	7	1·94	31·45
ST2	7′30″	9′30″	2′30″	8·31	8	0·98	23·67
ST3	3′50″	4′45″	3′10″	3·97	4	1·64	24·36
Shrub cover							
SC1	9′30″	10′30″	2′30″	9·20	6	0·83	25·56
SC2	5′30″	6′30″	4′30″	5·63	8	1·45	27·11

tp, time to ponding; *tr*, time to surface runoff; *ter*, time to the end of runoff after the end of the rain; *pr*, amount of precipitation necessary to generate surface runoff; *wfd*, mean wetting front depth; soil moisture content before (*Smb*) and after (*Sma*) the experiment

Table IV. Soil surface response to the simulated rainfall at each soil surface type, mean values (abbreviations as in Table III)

Soil units	*tp* (min s)	*tr* (min s)	*ter* (min s)	*pr* (mm)	*wfd* (cm)	*Smb* (%)	*Sma* (%)
Hillslope grass	5′46″	7′19″	2′10″	6·42	5·83	1·87	27·43
Bottom grass	5′50″	6′59″	3′59″	5·88	5·00	8·15	32·40
Tree covers	3′02″	4′26″	2′52″	3·80	6·17	1·83	28·76
Sheep trails	5′22″	7′15″	2′44″	6·39	6·33	1·52	26·49
Shrub covers	7′30″	8′30″	3′30″	7·41	7·00	1·14	36·34

Soil response to rainfall

Due to the previous drought period soil moisture content was very low. The amount of soil surface water (0–3 cm) on the slopes was lower than 2 per cent. Only the Bottom grass zone reached higher values with >8 per cent (Tables III and IV). No differences were found in relation to vegetation of litter cover.

The rain produced fast ponding (*tp*) at the soils beneath the trees (3 min 2 s on average), with the lowest value of 1 min 15 s observed in plot TC2. The other soil units showed a delayed ponding time with average values ranging from 5 min 22 s to 7 min 30 s, and high variation. At the Hillslope grass unit, the ponding time range from 3 min to more than 11 min. Runoff occurs 1 to 2 min after ponding (Tables III and IV).

The parameter *pr*, the amount of precipitation necessary to produce runoff, is very interesting. Beneath the trees, under the experimental conditions, 3·8 mm of rain is enough to produce runoff, whereas the other sites have thresholds of over 5 mm, even 6 mm in the Hillslope grass and 7 mm on the Shrub cover (Tables III and IV). Tree canopy is not taken into account here, although the study of the interception of the *Quercus ilex* is currently being studied.

Table V. Main soil hydrological characteristics at each plot

Plots	*Avr* (mm h^{-1})	*Rc* (%)	*fc* (mm h^{-1})	*Rc15* (%)	*Rc30* (%)
Hillslope grass					
HG1	36·65	69·38	8·91	35·58	55·98
HG2	11·13	21·08	37·61	1·44	12·50
HG3	24·05	45·53	15·17	10·04	27·17
HG4	13·31	25·20	33·17	2·41	14·05
HG5	31·14	58·95	18·18	36·77	50·83
HG6	21·61	40·91	27·01	22·70	33·46
HG7	23·45	44·39	24·13	19·65	34·37
HG8	36·75	69·57	12·42	47·57	62·13
HG9	15·33	29·01	36·10	17·96	25·28
Bottom grass					
BG1	27·80	52·63	21·48	30·67	45·22
BG2	26·52	50·21	20·70	21·50	39·10
BG3	7·87	14·91	43·23	3·24	10·50
Tree cover					
TC1	34·94	66·14	16·18	55·13	62·41
TC2	28·36	53·68	22·34	40·11	49·16
TC3	15·69	29·70	34·35	13·64	23·53
Sheep trails					
ST1	18·25	34·55	30·07	11·85	25·39
ST2	16·40	31·06	27·83	5·33	18·03
ST3	28·79	54·51	20·88	34·90	47·80
Shrub cover					
SC1	11·26	21·31	37·77	5·82	14·55
SC2	14·07	26·64	36·20	10·79	20·62

Avr, Average runoff rate; *Rc*, runoff coefficient; *fc*, steady-state infiltration rate; *Rc15*, runoff coefficient in the time interval 0–15 min; *Rc30*, runoff coefficient in the time interval 15–30 min

Table VI. Main soil hydrological characteristics for each soil surface type, mean values (abbreviations as in Table V)

Soil units	*Avr* (mm h^{-1})	*Rc* (%)	*fc* (mm h^{-1})	*Rc15* (%)	*Rc30* (%)
Hillslope grass	23·71	44·89	23·63	21·57	35·09
Bottom grass	20·73	39·25	28·47	18·47	31·61
Tree cover	26·33	49·84	24·29	36·29	45·03
Sheep trails	21·15	40·04	26·26	17·36	30·41
Shrub cover	12·67	23·98	36·99	8·31	17·59

Gravimetric soil moisture content after the experiments (53·6 mm of rain during 1 h) reached values of more than 26 per cent. The soils with the highest water retention capacity were the Hillslope grass sites (32·4 per cent), followed by the soils beneath Trees (28·8 per cent). The other three units achieved lower values: 27·4 per cent for the Herbs, 26·5 per cent for the Sheep trails and 26·3 per cent for the Shrubs. The latter ones probably have lower water retention capacity because of the higher amount of rock fragments.

The mean depth of the soil wetting fronts is quite homogeneous in average values for the five soil units. These range from 7 cm in the Shrubs and 5 cm in the Hillslope grass soil unit. Within each group, variability is very high, especially beneath the trees, and in the Hillslope grass, which is possibly related to varying grazing pressure within the same watershed (Table IV).

Main hydrological characteristics

Each soil unit shows high spatial variability of the main hydrological characteristics (Tables V and VI). Runoff coefficients at Hillslope grass range from 21 to 70 per cent. Except for the Shrubs, similar variation exists for the other soil units.

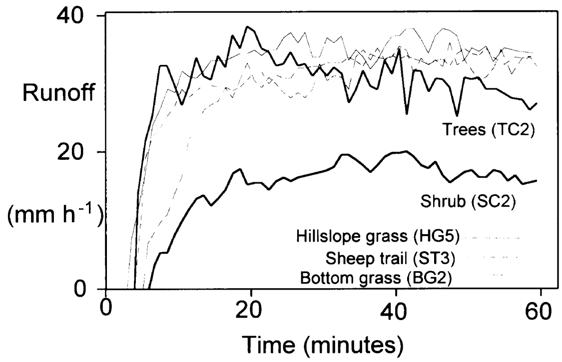

Figure 6. Typical runoff hydrographs of the five different soil surface types

In mean values, the average runoff rates (*Avr*) range from 21 to 26 mm h^{-1}, except for the Shrubs, where the *Avr* is lower than 13 mm h^{-1} (Figure 6). Runoff coefficients (*Rc*) vary between 39 per cent at the Bottom grass and 50 per cent beneath the Trees, whereas at Shrubs *Rc* is only 24 per cent. This high runoff rates are mainly due to the low steady-state infiltration rates found everywhere (24–28 mm h^{-1}), except for the Shrubs (37 mm h^{-1}). Also the low grazed area in the Bottom grass (plot BG3) has a large infiltration rate (43 mm h^{-1}), which indicates the importance of land management on soil hydrology.

The high runoff coefficients found in the watershed are related to the hydrophobicity of different surface types, especially beneath the trees. The maximum steady-state infiltration rate is reached very quickly, and normally a slight reduction occurs after 20 min of rain (plot TC2) (Figure 6). Only in the Shrub and Hillslope grass units is the angle of the runoff curve low, confirming a slow reduction of the soil infiltration rates.

Closer to reality are the parameters *Rc15* and *Rc30*, the runoff coefficients at the 0–15 and 15–30 min interval, respectively, because shorter thunderstorms are more frequent in the study area. As the parameters *Rc15* and *Rc30* show, runoff is very low during the first 15 min, except for the Tree sites, where, as a result of hydrophobicity, runoff is much higher (Tables V and VI). During the second 15 min (15 to 30 min) runoff is almost twice the value of the first 15 min (0 to 15 min). Shrubs always show lower runoff rates. Thunderstorms lasting more than 15 min and with comparable intensity will have much higher runoff production than those of shorter duration. The average runoff coefficient for the first quarter of the experiment is 20 per cent, whereas during the second quarter 32 per cent of the rain runs off.

Differences of soil response to rain between the units are illustrated by Tables V and VI, and Figure 6. The studied surfaces generate fast ponding and runoff and high runoff rates, except for the Shrubs, where runoff is lower and delayed. Soils beneath trees generate very fast runoff, the discharge peak is reached after 10 min, and runoff declines afterwards. This is the typical runoff curve found on hydrophobic soils, in which infiltration increases after reaching the runoff discharge peak due to a decrease of soil water repellency (Burch *et al*., 1989).

Wetting fronts

Although parameters like *Rc, fc* or *Wfd* usually explain the soils' hydrological behaviour, the shape of the wetting front can give more information about the infiltration process (Dunne *et al*., 1991). The wetting fronts reflect the high heterogeneity of the infiltration processes, and the large variability within the plot and between different soil units and land uses (Figure 7a–e), which is common on Mediterranean environments (Cerdà, 1995).

Under the tree canopy, the main wetting front is very shallow due to the repellent surface layer. This results in a negligible matrix flux infiltration, but in a large macropore flux, as the irregular-shaped circular secondary wetting fronts indicate (Figure 7a). The quick ponding and runoff discharge due to the hydrophobic substances of the top layer cause reinfiltration of the runoff through macropores, as observed during the field experiments and as demonstrated by Hendrickx (1990) for sandy soils.

Sheep trails develop more homogenous wetting fronts (i.e. ST1). Sometimes, wetting front shapes are irregular due to the trampling variability where the infiltration rates are higher (ST2). Even very irregular

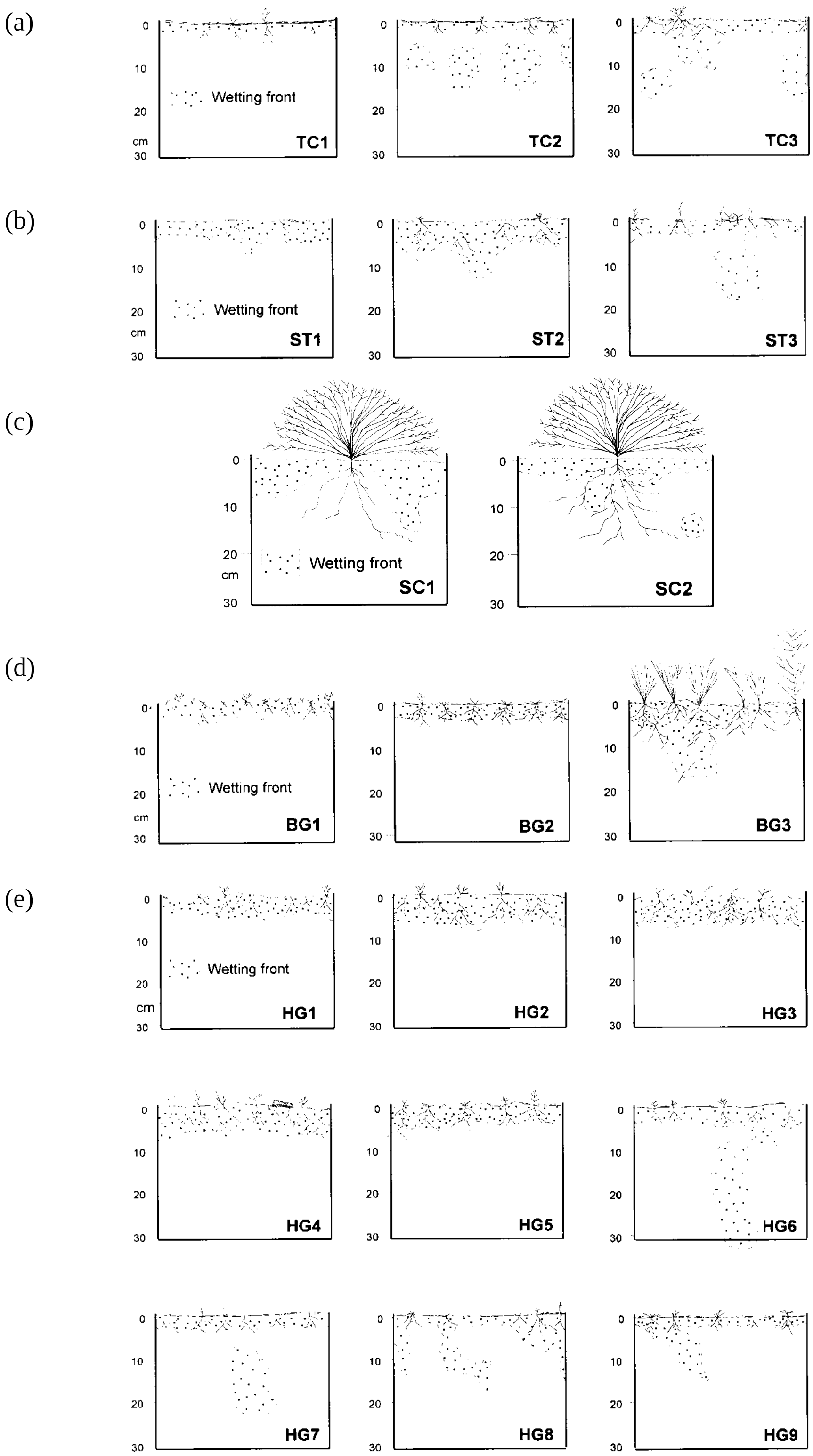

Figure 7. Pattern of the wetting front (dashed curve) after 53·6 mm of rain during 1 h. (a) Beneath trees (*Quercus ilex*): Tree cover. (b) Sheep trail. (c) Shrub cover (*Lavandula pedunculata*). (d) Herb cover on the bottom valley accumulation: Bottom grass. (e) Herb cover on the slope: Hillslope grass

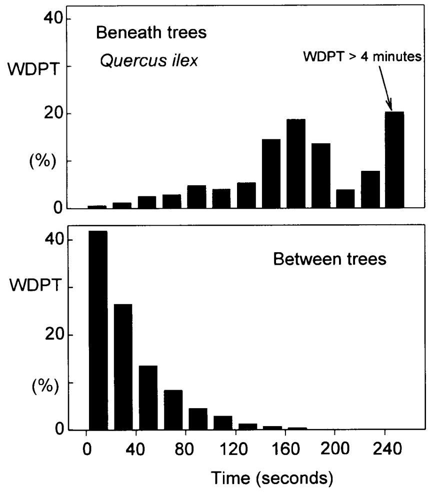

Figure 8. Frequency distribution of the WDTP at the surfaces beneath and between the trees (*Quercus ilex*)

wetting fronts due to the macropore fluxes which originated in the trampling area can be found (plot ST3) (Figure 7b).

The Shrub unit shows a special behaviour under rainfall. Both cases, SC1 and SC2, have very heterogeneous wetting fronts, but their shapes are different. In the first one, deeper infiltration is reached on the shrub-bare border, contrasting with the second one, where more water is concentrated below the centre of the plant (Figure 7c). Probably macropore flow of microtopography are responsible for this difference. However, infiltration has a higher heterogeneity under shrub cover than under other cover types.

At the Bottom grass zone, two plots (BG1 and BG2) show very shallow and homogeneous wetting fronts. They represent the overgrazed situation, where the soil surface is more compact. The third example, BG3, is of the same soil type, but under low grazing pressure. There, infiltration is deeper and the heterogeneity of the wetting front higher (Figure 7d).

The Hillslope grass unit shows great variation of wetting front shapes due to the high number of factors interacting. Some of the plots show a very homogeneous and shallow wetting front (HG1–HG5). This is the shape expected in an area where matrix infiltration is most important. However, macropore fluxes are shown to be important in some places, where nests of ants and spiders exist (HG6 and HG7). Furthermore, at sites ploughed in the past and abandoned about 30 years ago, the shapes of the wetting fronts are sometimes irregular (HG6) (Figure 7e).

The influence of Quercus ilex *trees on soil water repellency*

In order to measure the importance of soil hydrophobicity beneath the *Quercus ilex* canopy, as indicated by the runoff hydrographs (Figure 6), the WDPT test was carried out at surfaces beneath trees and in the open areas. The results show that the soil surface under tree canopy shows on average more repellency than between trees (Figure 8). There, after 4 min, close to 20 per cent of the drops 'ball up', as Letey (1969) described it. Only 1 per cent of the drops were observed before 10 s, which in the terms of Adams *et al.* (1970) is a non-repellent soil. Nevertheless, less than 4 per cent of the drops were observed before 1 min and more than 95 per cent resisted for more than 1 min – slight repellency and strong repellency, respectively – using the classification of Adams *et al.* (1970) and McGhie and Posner (1980). BeBano (1981) suggests that a soil water-repellent if the water drop does not infiltrate immediately or within 5 s.

In the open areas of the Dehesa, soil water repellency is low in comparison with the *Quercus ilex* sites. More than 40 per cent of the drops were absorbed before 20 m and 72 per cent of them before 10 m. Another group of samples (40 per cent) corresponds to the slightly water-repellent soils, where the drops ball up for less than 1 min but more than 20 min. Strongly water-repellent soils also exist in the open areas (>60 min), but this is less than 20 per cent of the sample (Figure 8).

DISCUSSION

The differences within each soil unit are very large. This feature is typical on the Mediterranean ecosystems at the scale of measurement (plots of $0{\cdot}25\,m^2$). This is probably due to the very high rainfall intensity performed, which should increase differences between sites (Dunne *et al.*, 1991). Under very low rainfall intensities the differences between plots are negligible.

It has to be taken into account that the data presented were gathered under very dry conditions during a drought period. This situation is probably in part responsible for delayed ponding (>6 min on average) and runoff initiation (>7 min on average) in the non-repellent or slightly repellent soils of the Shrubs, Sheep trails, Hillslope grass and Bottom grass, unlike sites located beneath the Trees which show a very high water repellency and generate ponding and runoff very quickly. The drought can also be responsible for the low water acceptability beneath the trees as was pointed out by Crockford *et al.* (1991) in a dry sclerophyllous eucalyptus forest in Australia. This low water acceptability contributes to higher runoff rates, as other works have demonstrated (McGhie, 1980).

In this paper, particular attention is given to the role of soil water repellency because it can be the key factor in soil and hillslope hydrology during intense thunderstorms in the Dehesas during droughts and the summer season. The substances responsible for soil water repellency are mainly generated by the vegetation (Scholl, 1971; DeByle, 1973; Dyrness, 1976; Giovannini and Lucchesi, 1984; McGhie and Posner, 1981) or due to fire (Everett *et al.*, 1995). Decomposing plant parts containing hydrophobic substances, accumulated at the boundary between organic and mineral soil layers, create a non-wettable layer (DeBano *et al.*, 1976). This hydrophobic layer is strongly developed under *Quercus ilex* canopies, as the hydrological response has demonstrated.

In comparison with other soils from semi-arid areas, infiltration rates in the Dehesa are very low. In rangeland zones of southeast Spain, with underlying sandstones, limestones, clays and marls, infiltration rates are greater than in the soils developed on schists of the Guadalperalón catchment under comparable moisture conditions (Cerdà, 1995). In northern Israel (unpublished data), in semi-arid areas of Australia (Bonell and Williams, 1986), and in the Arizona and New Mexico deserts (Wilcox *et al.*, 1988; Ward and Bolin, 1989) measured infiltration rates were also higher.

Even soils affected by forest fires, with hydrophobic characteristics, have higher infiltration rates than those of the study area (DeBano *et al.*, 1976; Giovannini *et al.*, 1988). In spite of the lack of vegetation, burnt soils can absorb more than 90 per cent of the rain produced with simulation experiments similar to the ones presented here (Cerdà, 1933a). In northeast Spain, Imeson *et al.* (1992) found signs of water repellency at most of the sites studied, in both unburnt and burnt forest. However, infiltration rates were always quite high and the time to runoff delayed. In other burnt rangelands, lower runoff than in the Dehesa is related to better soil quality, with higher infiltration even after fires (Calvo and Cerdà, 1994; Cerdà *et al.*, 1995).

The negative influence of grazing livestock on infiltration has been demonstrated (Warren *et al.*, 1986a,b; Weltz and Wood, 1986; Weltz *et al.*, 1989). In the overgrazed areas of the Dehesa, infiltration is less than half of that produced in the low-grazing-pressure area in the same geomorphological position (valley bottom accumulation). Droughts, together with the grazing livestock, are shown to produce a strong decrease of the herbaceous cover in the study area, favouring an increase of bare and crusted soils (Bernet *et al.*, 1994; Schnabel *et al.*, 1996). As a result, increased runoff is expected as has been demonstrated by other authors (Morgan, 1986; Elwell and Stocking, 1976; Lee and Skogerboe, 1985; Woo and Luk, 1990; González, 1992). Also, the higher hydrophobic response under *Quercus ilex* canopy must be mentioned. Under natural rainfall, the throughfall and stemflow at the Dehesa probably increase soil water repellency due to changes in the rainfall chemistry, as Crockford *et al.* (1991) have demonstrated in Australia.

The situation found during the field experiments in May 1995 was that of a persistent drought with low vegetation cover. Soil hydrophobicity was very high. Soil water repellency can contribute to flash floods in the watershed as Burch *et al.* (1989) have shown. It is possible that the unfavourable conditions during prolonged dry periods intensify soil hydrophobicity. As a consequence, one could expect temporal variations of this characteristic, and hence varying infiltration rates. Therefore, the experiments must be repeated, not only during the humid season, but also when the area receives higher annual rainfall amounts, causing a denser

vegetation cover. As strong interannual rainfall variability is a common feature in the study area (Schnabel, 1995), as well as in other semi-arid areas, the interrelationships between precipitation, vegetation, grazing and top layer hydrophobicity, on one hand, and their influence on slope and catchment hydrology, on the other hand, deserve further investigation.

It is striking that different vegetation cover influences soil hydrology in different ways. The Shrub-covered soils have the highest infiltration rates. These data confirm shrubland as a stable cover, as mentioned by Thornes (1976, 1990), and the positive influence of the flora and microflora on water infiltration (Bond and Harris, 1964). The high rock fragment cover of the Shrub sites may favour infiltration. The positive effect of rock fragments on infiltration was demonstrated under laboratory conditions (Poesen and Ingelmo, 1992) and under field conditions (Agassi and Levy, 1991). Moreover, the macropore fluxes are higher when the shrub grow (flow along roots or dead roots).

Water-repellent soils in the Guadelperalón catchment have higher runoff rates and steeper runoff curves. This is due to quick ponding and runoff generated by the hydrophobic substances. Moreover, as the wetting fronts demonstrate, infiltration is controlled by preferential flow. Hydrophobicity causes greater surface runoff, which becomes available for subsequent infiltration into the macropore network.

This paper confirms the importance of spatial discontinuities for hillslope runoff. The non-uniform infiltration and the influence of the vegetation and the sheep trails result in very discontinuous runoff generation, which is also influenced by water repellency. Small areas may produce runoff, which in large areas infiltrates afterwards, due to the existence of macropores and more permeable soils. This has been found also in other Mediterranean rangelands, where fires cause soil hydrophobicity (Imeson *et al*., 1992). In more arid areas, as in the Negev desert, the spatial discontinuity of runoff is determined by regolith and soil characteristics (Yair and Lavee, 1985). In the Dehesa ecosystem, runoff processes are discontinuous and spatially structured by the effects of water repellency and vegetation distribution during the drought period.

It seems clear that the discontinuous pattern of infiltration created by hydrophobic substances and macropores constitutes an effective system for trapping hillslope water and providing deeper infiltration. This water is easily conserved against evaporation and used by plants during dry periods. As Imeson *et al*. (1992) demonstrate in La Selva (Girona, Catalonia), discontinuous flow patterns on the slopes are not random. In the Dehesa catchment runoff patterns are closely linked with vegetation patterns as in other Mediterranean ecosystems (Cerdá, 1995).

CONCLUSIONS

At the Guadalperalón catchment, soil water repellency greatly reduced infiltration. The soil beneath *Quercus ilex* canopies is the most water-repellent in the experimental basin, causing fast ponding and runoff, and higher runoff rates. The shrub-covered soils have the highest infiltration rates, whereas the sheep trails and the grass-covered slopes and valley bottoms produced high runoff rates.

The low vegetation cover as a result of a persistent drought and grazing pressure, together with the water repellency of the soils, is responsible for the generally low infiltration rates in the Dehesa. In spite of this, macropore fluxes were found in different locations. Beneath trees, shrubs and at soils with herbaceous cover, preferential macropore fluxes are more important than in the bare areas. The discontinuity of the runoff fluxes produced by hydrophobicity enhances macropore fluxes and deeper infiltration.

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